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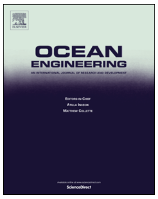

Pitch motion mitigation of spar-type floating substructure for offshore wind turbine using multilayer tuned liquid damper

Minho Ha, Cheolung Cheong*

School of Mechanical Engineering, Pusan National University, Busan 609-735, Republic of Korea

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ABSTRACT

The possibility of controlling the pitch motion of a spar-type floating substructure for offshore wind turbines by using a tuned liquid damper (TLD) was numerically investigated. First, the motion of a spar-type substructure scale model excited by surface waves was predicted, and the results were compared to the measured data. There was reasonably good agreement between the two results, which confirmed the validity of the present numerical methods. Then, the effects of a TLD on the motion of the floating substructure were quantitatively assessed by a comparison between the predicted results with and without a TLD. The pitch motion of the scale model could be reduced by using a TLD. Based on this result, multilayer TLDs were proposed to effectively reduce the pitch motion of the floating substructure at the fixed target frequency. This expectation was confirmed when the predicted results were compared with that of the single-layer TLD. Finally, a theoretical model was derived to compute the rate of reduction in the pitch motion of floating substructures depending on the number of TLD layers. This model allowed the minimum number of layers for TLDs to reduce the pitch motion of the substructure by the required amount to be determined.

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1. Introduction

Increasing interest in renewable energy has led to continuous growth in the wind turbine market. The global installed wind power capacity reached approximately 318 GW in 2013. However, environmental problems such as noise and the visual impact on the landscape have prevented inland wind turbines from becoming widespread. As an alternative, offshore wind farms are gaining attention (Kaldellis and Kapsali, 2013); the first offshore wind farm was installed in Denmark in 1991. The global offshore wind power capacity is expected to reach a total of 75 GW by 2020. As the next generation of offshore wind turbines, a floating wind turbine comprising a floating substructure and turbine on its top side has received increasing interest because the deployment of existing offshore fixed-bottom wind turbine technology has been limited to water depths of 30 m, while the global deep-water wind resources are extremely abundant in subsea areas with depths of up to 600 m (Archer and Jacobson, 2005). Despite this merit, there are many technical problems to resolve before commercialization. One of most important is that a floating wind turbine is more readily exposed to external sources of excitation, such as wind, waves and currents, than bottom-fixed turbines (Butterfield et al., 2007). These excitations causes translational and rotational motions of floating substructures which may have adverse effects on the performance of wind turbines on their top side. Therefore, effective methods or devices to reduce these motions are essential for wide-spread of off-shore floating wind turbines.

One approach is based on the extension of pitch control strategy which was originally used to control aerodynamic load in wind turbines to mitigate the effects of the motions of floating substructures. Larsen and Hanson (2007) presented a control method including the tuning method to ensure the desired control frequency lower than the lowest critical tower frequency related to the rigid body motion of the spar-type substructure. Namik and Stol (2010) developed a periodic state space controller which utilizes individual blade pitching to creates asymmetric aerodynamic loads and thus to increase the platform restoring moments. Li et al. (2014) applied adaptive output feedback control to collective pitch control and load mitigation. The performance of this control was shown to be better than gain scheduling PI controls and disturbance accommodating control. However, these methods based on pitch control require more complex control strategy which inevitably requires tradeoff between power performance and loads mitigation. The other group is based on direct vibration control strategy by using so-called vibration absorbers. Performance of a ball vibration absorber for offshore wind turbines was experimentally investigated by Li et al. (2012). The use of tuned mass damper (TMD) is suggested by Murtagh et al. (2008)

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* Corresponding author. Tel.: +82 51 510 2311.
E-mail address: ccheong@pusan.ac.kr (C. Cheong).

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and Si et al. (2014). Colwell and Basu (2009) employed a tuned liquid column damper (TLCD) as the vibration observer. However, all of these studies focus on the motion mitigation of bottom-fixed offshore wind turbines by using the vibration absorbers.

This paper proposes using multi-layer tuned liquid dampers (TLDs) as an effective method to reduce the pitch motion of a floating wind turbine caused by external forces; in this study, their effectiveness was quantitatively investigated.

A TLD is a tank partially filled with liquid and has been used in tall buildings to reduce the effects of seismic waves (Kareem and Kijewski, 1999). If a TLD is subjected to external forces, the liquid in the TLD starts sloshing and generates reaction forces that can reduce the effects of external forces. The amplitude of reaction force by sloshing is proportional to the mass of water in TLD, and sloshing phenomena have natural frequencies that depend on the liquid height and internal dimensions of the tank (Seo et al., 2012). This implies that the maximum reaction force may be generated at the sloshing natural frequency. Therefore, setting the natural frequency of a TLD to be the same as the frequency of the external force should maximize the reduction in the motion of the structure.

The authors (Ha et al., 2012a, 2012b) previously validated a numerical method based on unsteady Reynolds-averaged Navier–Stokes (RANS) solvers by using the volume of fluid (VOF) method (Hirt and Nichols, 1981) to simulate internal sloshing phenomena in a TLD. This numerical method was used to investigate the effects of the TLD on the motion of a rectangular floating body subjected to water surface waves (Ha and Cheong, 2013). The results showed that the surge motion of the floating body can be reduced by using the TLD. The present paper is an extension of these studies and considers the effects of a multilayer TLD on the motion of the substructure for a floating wind turbine. First, to validate the given numerical methods, the predicted motion of a floating substructure without a TLD was compared to the measured data. Then, motions of a scale model with and without a TLD were computed. The results were compared to quantitatively assess the effects of the TLD. The multilayer TLD is proposed to generate a greater reaction force than the single-layer TLD without changing the natural frequency. The predicted motions of the floating substructure with single- and multilayer TLDs were compared to demonstrate the effectiveness of the latter. A theoretical model was derived to predict the rate of reduction in the pitch motion of a floating substructure depending on the number of layers of the TLD. The theoretical model was validated through a comparison of its predicted results with the numerical results. The results showed that the model can be used to determine the optimum number of layers for a multilayer TLD to reduce the pitch motion of the substructure by the required amount in the design state.

The main contributions of the current paper are three-fold. First, first-principle-based numerical methods are employed to investigate the effect of TLDs on the motion of a spar-type floating substructure. The methods are based on the fluid–structure interaction simulations where the motions of fluids are predicted by solving unsteady Reynolds-averaged Navier–Stokes equations and the motion of the solid substructure is computed by considering the force exerted by the fluids on it. Second, based on the simulation results, the multi-layer TLD is newly proposed to suppress the pitch motion of the floating substructure more effectively without changing target natural frequency. Third, a theoretical model is developed to quantify the effect of the number of layers of the TLD on the pitch motion of the spar-type substructure. This model can be used as an effective tool for determining the optimum number of layers of TLD to control the pitch motion of the substructure.

All theoretical models relevant to subsequent numerical simulations are described in Section 2. The detailed conditions of scale-model experiments and numerical simulations are presented and their results are compared in Section 3. This confirms the validity of the current numerical methods. Numerical simulation results are presented to investigate the effects of multi-layer TLDs on the motions of spar-type floating substructures in Section 4. A theoretical model is developed to quantify the effects of the number of layers in a TLD on the pitch motion of a spar-type floating substructure in Section 5.

2. Theoretical models

In this section, theoretical models which are relevant to subsequent numerical simulations are introduced. Firstly, a theoretical model for generating surface wave in a water basin is described. This is used as boundary conditions to generate water surface waves of the given amplitude and frequency in following numerical simulations. Secondly, a theoretical formula for the natural frequencies of inner sloshing is derived to tune the natural frequency of TLD to the target frequency. Thirdly, governing equations used to simulate the motions of a floating-substructure subject to water surface waves are described.

2.1. Virtual water basin

The background theories needed to set up the boundary conditions for predicting the motion of a floating substructure in a virtual water basin are described here.

Fig. 1 shows a surface wave and the related boundary conditions that allow the problem of interest to be a boundary value problem. Under the assumption of an inviscid, irrotational, and incompressible flow, the governing equation can be derived as Laplace's equation for the velocity potential in the following form:

$$\nabla^2\phi = 0. \tag{1}$$

The wall boundary condition is applied to the bottom. This means that the normal velocity on the bottom is zero:

$$w = 0. \tag{2}$$

The kinematic and dynamic free surface boundary conditions are given as follows:

$$-\frac{\partial\phi}{\partial t} = \frac{\partial\eta}{\partial t} - \frac{\partial\phi}{\partial x}\frac{\partial\eta}{\partial x} \tag{3}$$

$$-\frac{\partial\phi}{\partial t} + \frac{1}{2}\left[\left(\frac{\partial\phi}{\partial x}\right)^2 + \left(\frac{\partial\phi}{\partial z}\right)^2\right] + g\eta = C(t) \tag{4}$$

The lateral boundaries are set to be periodic in space and time:

$$\phi(x,t) = \phi(x+L_w,t) \tag{5a}$$

$$\phi(x,t) = \phi(x,t+T) \tag{.5b}$$

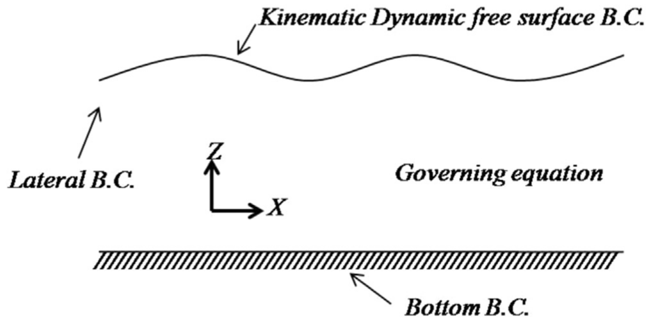

Fig. 1. Applied boundary conditions to derive potential function for surface wave.

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